

****Volume Title****

*ASP Conference Series, Vol. **Volume Number***

****Author****

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Optical observations of PSR J1357–6429 field

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Abstract. PSR J1357–6429 is a Vela-like radio pulsar that has been recently detected with *Chandra* and *Fermi*, which, like Vela, powers a compact X-ray pulsar wind nebula and X-ray-radio plerion associated with an extended TeV source. We present our deep optical observations with the Very Large Telescope to search for an optical counterpart of the pulsar and its nebula. We detected a point-like source in *V*, *R*, and *I* bands whose position is in agreement with the X-ray position of the pulsar, and whose colours are distinct from those of ordinary stars. The tentative optical luminosity and efficiency of the source are similar to those of the Vela pulsar, which also supports the optical identification. However, the source spectrum is unusually steep, with a spectral index of about 5, which is not typical of optical pulsars. The source offset from the radio position of PSR J1357–6429, which is in line with the corresponding offset of the X-ray position, implies the pulsar transverse velocity of 1600–2000 km s^{−1} at the distance of 2–2.5 kpc, making it the fastest moving pulsar known.

1. Introduction

PSR J1357–6429 is a young (characteristic age $\tau = 7.3$ kyr) and energetic (spin-down luminosity $\dot{E} = 3.1 \times 10^{36}$ ergs s^{−1}) 166 ms radio pulsar that was discovered in the Parkes multi-beam survey of the Galactic plane (Camilo et al. 2004). At a distance of 2.4 kpc estimated from its dispersion measure (DM), it is one of the nearest young pulsars known. This proximity has motivated further observations of the pulsar field in different spectral domains.

The X-ray observations with *Chandra* and *XMM-Newton* have revealed an X-ray counterpart of the pulsar and a tail-like pulsar wind nebula (PWN) (Esposito et al. 2007; Zavlin 2007; Chang et al. 2012; Lemoine-Goumard et al. 2011) and have firmly established X-ray pulsations (Chang et al. 2012; Lemoine-Goumard et al. 2011). Periodic pulsations of PSR J1357–6429 were also discovered in the GeV range with *Fermi* (Lemoine-Goumard et al. 2011). A fainter extended X-ray plerion was detected on a

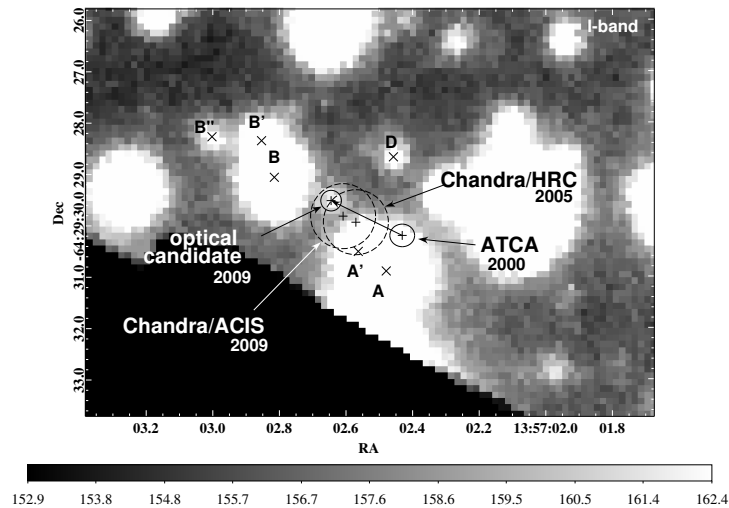


Figure 1. The fragment of the VLT *I*-band image. The 1σ error ellipses of the X-ray and radio positions of the pulsar are shown. The position of the possible optical counterpart and its uncertainties are also indicated along with possible pulsar proper-motion path. Background sources located near/along this path are also marked.

few tens of arcminutes scale (Chang et al. 2012; Abramowski et al. 2011) which positionally coincides with an extended TeV source, HESS J1356–645 (Abramowski et al. 2011). The TeV source is associated with the pulsar, and a radio plerion, a supernova remnant (SNR) candidate, catalogued as G309.8–2.6.

The age and observational properties of the J1357–6429 pulsar/PWN system appear to be similar to the Vela pulsar system, which is about ten times closer to us and much more comprehensively studied in various spectral domains. In contrast to Vela, the J1357–6429 field has not been studied in the optical. To search for an optical counterpart of the J1357–6429 pulsar/PWN system, we carried out the first deep observations of its field with the ESO Very Large Telescope (VLT) in *VRI* bands. For details of observations and data reduction see Danilenko et al. (2012) while main results and conclusions are presented below.

2. Selection of a counterpart candidate

A fragment of the VLT *I*-band image presented in Fig. 1 depicts vicinity of the pulsar. At least three, *A*, *A'*, and *C*, of the nearby objects marked in Fig. 1 can be considered as potential optical counterparts of the pulsar. Object *A* has been already analysed and qualified as a mere main sequence star by Mignani et al. (2011) based on a part of our VLT data. To select a most plausible candidate to the optical counterpart of the pulsar we performed the PSF photometry on our *VRI* images and constructed colour-colour and colour-magnitude diagrams and the former one is presented in Fig. 2 while the rest can be found in Danilenko et al. (2012). Colours of the object *C* differ from colours of the most part of the field stars but compatible with ones of some other pulsar optical

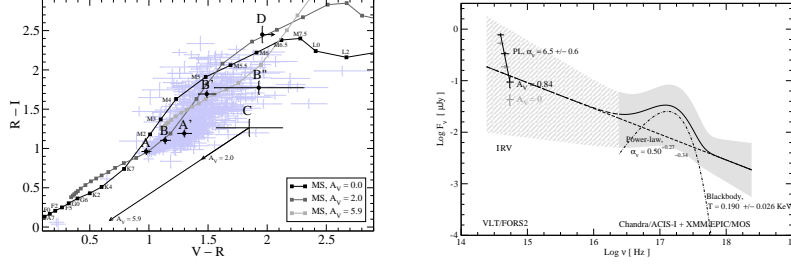


Figure 2. *Left:* The colour-colour diagram of PSR J1357–6429 field stars. The candidate labelled by C and nearby stars marked in Fig. 1 are shown. Empirical main-sequence curves reddened with a zero, medium, and entire Galactic extinction, $A_V = 0, 2.0$, and 5.9 , are shown. *Right:* Multi-wavelength unabsorbed spectrum for PSR J1357–6429. The best fits to the X-ray spectrum, including thermal and non-thermal components, are shown along with the observed and dereddened optical fluxes.

counterparts usually detected as faint blue objects, like, for instance, the Geminga-pulsar optical counterpart (Shibanov et al. 2006).

Besides that, among the other potential candidates, the spatial position of object C is most closely compatible with the X-ray position of the pulsar obtained from the ACIS-I observations taken in the same year as the optical data. All the above allows us to keep it as the only likely optical counterpart of the pulsar J1357–6429.

If it is indeed the counterpart, this implies at least two prominent properties of the pulsar.

3. Unusually steep spectrum

The multi-wavelength spectrum constructed from the *VRI* fluxes of the counterpart and the X-ray data reanalysed by us (Danilenko et al. 2012) is in Fig. 2. The optical fluxes were dereddened with extinction, A_V , of 0.8 based on hydrogen column density, N_H , estimated by means of BB+PL fit to the X-ray data (Danilenko et al. 2012). The putative counterpart has an extremely red spectrum which is atypical of pulsars and raises doubts about the pulsar nature of the candidate. Several possible explanations of the spectrum steepness were proposed by Danilenko et al. (2012).

We also estimated the counterpart optical luminosity (in the *V* band) of 1.5×10^{29} ergs s $^{-1}$, and efficiency, $\eta_V = L_V/\dot{E}$, of 4.8×10^{-8} , to be close to that of the Vela pulsar, which has similar age and is known to be inefficient in the optical and X-rays (Zharikov et al. 2006). The counterpart L_X/L_V ratio of about 100 is also in the range of 100–1000, typical of pulsars. All that are indirect evidence in favour of the real identification of the counterpart candidate with the pulsar.

4. Very high proper motion

A significant offset of the counterpart candidate position from the J1357–6429 radio coordinates measured 8.7 yr earlier, $1''.54 \pm 0''.32$ (Fig. 1), suggests that the pulsar has a high proper motion. At the most plausible distance range of 2–2.5 kpc, which follows from the A_V –distance relation and N_H estimated from the X-ray data (Danilenko et al.

2012), this implies the pulsar transverse velocity to be between $1690 \pm 350 \text{ km s}^{-1}$ and $2110 \pm 440 \text{ km s}^{-1}$. The value is opposed to a two-to-three times smaller value based on a 7 arcmin offset of the pulsar from the centre of the extended source HESS J1356–645 (Abramowski et al. 2011). But, the difference between two estimates can be reconciled by assuming that the true age of J1357–6429 is twice as small as the characteristic one, and two ages may differ by at least 40% (see, e.g. Briskin et al. 2003). The direction of the putative proper motion is nearly consistent with the direction of the 7 arcmin offset and with the NE extension of the tail-like PWN structure detected in X-rays (Chang et al. 2012; Zavlin 2007). Besides that, a significant difference between the radio interferometric (Camilo et al. 2004) and X-ray pulsar positions obtained at different epochs is also indicative of a proper motion of the pulsar as noted by Mignani et al. (2011). From Fig. 1, one can see that the *Chandra*/ACIS position is apparently shifted from the *Chandra*/HRC one, in line with the suggested motion, although the shift is of a low significance.

To our knowledge, the highest pulsar velocity of $1080 \pm 100 \text{ km s}^{-1}$, which has been firmly established by direct proper-motion and parallax measurements with the VLBA, belongs to PSR B1508+55 (Chatterjee et al. 2005). The distance to that pulsar, $2.37 \pm 0.20 \text{ kpc}$, is comparable to that of J1357–6429, which suggests that similar direct measurements are also possible for the latter. To confirm the high proper motion, it is necessary to repeat radio observations performed with the ATCA (Camilo et al. 2004) once again and then, if the high proper motion is confirmed, to perform parallax measurements with the VLBA to confirm the distance to PSR J1357–6429. As a result we may establish the fastest pulsar ever known, which is important for understanding the nature of high velocities of pulsars (see, e.g. Chatterjee et al. 2005). These observations would also be of a great complement to the approved VLT/NACO high spatial resolution adaptive optical observations of the pulsar field and they can firmly confirm the optical counterpart by comparing the proper motion measurements in the optical and radio ranges.

Acknowledgments. The work was partially supported by the Russian Foundation for Basic Research (grants 11-02-00253 and 11-02-12082), Rosnauka (Grant NSH 4035.2012.2), and the Ministry of Education and Science of the Russian Federation (Contract No. 11.G34.31.0001). SZ acknowledges support from CONACYT 151858 project, GP was partly supported by NASA grant NNX09AC84G, and REM acknowledges support by the BASAL Centro de Astrofísica y Tecnologías Afines (CATA) PFB–06/2007.

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